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FOREIGN TECHNOLOGY DIVISION

AIR FORCE SYSTEMS COMMAND

INTERNATIONAL AVIATION

(Selected Articles)

FOREIGN TECHNOLOGY DIVISION

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DEVELOPMENT AND TECHNICAL LEVEL OF INTERCEPTOR PLANES IN THE USSR

Wu Yongzhi

Since World War II, the development of interceptor planes in the USSR has been relatively rapid, with frequent change of developmental generations and apparent improvement of quality. At present, the number of varieties and aircraft of fighter planes deployed by the USSR is greater than that of the Western countries. There are altogether 16 varieties of interceptor planes (including the air control interceptors, air cover interceptors, and ground attack planes) deployed by the various military services of the USSR; the number of remolded versions is not included in the 16 varieties. The total deployment of military aircraft numbers more than 7,300, which considerably exceeds that of the United States.

After World War II, the interceptor planes in the USSR went through two development stages from technical acquisition to independent development, and from low-level to high-level development. In the early 1950s, the first generation of jet interceptors was independently developed in the USSR, entering the supersonic era simultaneously with the Western countries. By now, three generations of interceptors have been deployed in the USSR; the fourth-generation interceptors will be soon deployed by the military services.

I. The First Stage of Development: Beginning With Technical Acquisition

In World War II, speed, maneuverability and firepower of the Soviet interceptors attained a certain level. In the later stage of the war, Nazi Germany prematurely deployed its first batch of jet fighter planes onto the battlefield; these interceptors with new power plants had an apparent speed superiority, which was given much attention by the USSR, as it consistently stressed the flight speed and altitude. In December 1945, a development plan for jet technology was prescribed by the USSR, planning to develop (all Soviet designed) jet interceptors with five to six years of development time. At that time, Germany and Britain were leading the world in jet technology, therefore the Soviet Union prescribed that the learning of foreign experiences and acquisition of foreign technology were considered the central theme of the development. The plan prescribed three developmental directions.

The first developmental direction was to utilize available foreign jet engines in designing new aircraft. During the war, the Soviets captured some Yuemo [transliteration]-004 and BMW-003 jet engines from Germany; these jet engines were named by the Soviets RD-10 and RD-20, with thrusts at 850 and 800 kilograms. In the USSR, the mission of designing new aircraft by using these jet engines was simultaneously assigned to four aircraft design bureaus; it was required that two models would be of single engine type and the other two models, twin engine type. In 1946, Yak-15 and MiG-9 were selected for batch production and deployment in military services.

The second developmental direction was to have the Soviet factories buy patents and production licenses of foreign jet engines to design new aircraft. In 1947, through trade negotiations the Soviets obtained production licenses of two (Ni'en and Devente [both are transliterated]) centrifugal turbojet engines from Rolls-Royce Company of Britain. In addition, 25 and 30 turbojet engines of these two models were purchased, with Soviet model numbers RD-45 and RD-500. Along this developmental direction, the MiG-15 aircraft with RD-45 engine installed and the La-15 and Yak-23 aircraft with RD-500 engine installed were successfully designed. The MiG-15 planes were completed with test flights in 1947 and mass production soon afterwards.

The third developmental direction was to utilize foreign experiences, foreign data, and foreign experts (mainly German prisoners of war) alongside

Soviet efforts in succeeding to independently design jet engines. On this technical foundation, aircraft were independently designed. Thus, the Yak-25 and MiG-19 were successfully designed and test flights were completed in 1952 and 1953. Both of these models entered mass production.

Thus, the Soviets completed in 1953 the transition to independently developed jet engines for interceptors. Both the MiG-19 and Yak-25 are the first generation interceptors of the USSR. The Yak-25 is capable of limited all weather combat capability. Weapons carried by Soviet interceptors began the transition from aircraft guns and rocket bombs to air-to-air guided missiles. Soon afterwards, air-to-air missiles guided by wave beams began their deployment.

II. The Second Stage of Development: From Low Level to High Level Technology

The MiG-19 and Yak-25 are the first-generation interceptors that the Soviets independently developed; quite a few installations on these models were not satisfactory, such as the onboard equipment, life saving system and weapon system, while the flight speed was not sufficiently high. In addition, some new problems appeared in the combat experiences of the world's first jet fighter combat in the Korean War. Therefore, the Soviets immediately developed the second generation without accumulating more experience with the first-generation interceptors. Only two to three years after the test flights of the first-generation interceptors, the second-generation interceptors appeared, such as the MiG-21, Su-7 and Su-9. Two years later, the Tu-28 appeared. Thus, the second generation interceptors of the USSR became a series of multiple models to basically meet the requirements of the time. Compared to the first generation, the second generation had apparent improvements, attaining flight speeds twice the speed of sound and all weather combat capability with more onboard equipment and greater aircraft weight. There were twin-seat long-range interceptors and ground attack bombers. The air-to-air guided missiles with semi-automatic radar guidance and infrared guidance began to be deployed in the military services.

Many tasks and various improvements were done on the second generation interceptors in the USSR. The improvement experiences of the MiG-21 were known to all; there are 18 major model changes. The most recent model change (BC model of MiG-21) is still in production at present, with continuous production of MiG-21 for 25 years. By adopting the sweptback wing technique, the Su-7 was improved

into the Su-17, Su-20 and Su-22. The Su-9 was improved into the Su-11 by enhancing the onboard equipment and weapon system as well as increasing engine thrust. In addition, for improving ground survival capability of interceptors, in the mid-1950s the Soviets began to develop the vertical takeoff and landing technique for aircraft. In 1957, an experimental flight platform capable of vertical takeoff and landing began test flights to accumulate data and experiences for vertical takeoff and landing jet interceptors.

Although the Soviets attained considerable successes in its second-generation interceptors, these planes still had apparent deficiencies when compared with world standards, such as lower maximum speed, shorter navigation range, crude onboard equipment, insufficient firepower of the weapon system, and insufficient attack loads and low-altitude penetration capability. Then, in the early 1960s, the third-generation interceptors began to be developed. In the years 1964-1966, MiG-23, MiG-25, Su-15, and Ziyoutu [transliteration] Yak vertical takeoff and landing interceptors were developed. In 1970, the Su-24 was developed. The MiG-27 was the improved version of MiG-23; the Yak-36 was the improved version of the Ziyoutu model. The characteristics of this generation of interceptors are as follows: further improvement of maximum flight speed (breaking the thermal barrier in the case of the MiG-25), improvements in low-altitude and low-speed performance, significant increase in combat radius, strengthening of onboard equipment and weapon system, applications of high-performance onboard radar and air-to-air missiles, all-direction attack capability beyond the line-of-sight distance, and considerable strengthening of attack load carrying capacity and low-altitude penetration capability. In the generation of considerably improved design technique were variable sweptback wings, adjustable type twin air intake system, and vertical takeoff and landing; these techniques attained a relatively high level.

In the Vietnam War, combat experiences for the first-series supersonic fighter planes were gained. This explains that at the present onboard equipment and weapon-system level, the dogfight air combat is not out-of-date. Thus, an aircraft's maneuverability is very important. However, in this aspect there is an apparent technical gap between the third-generation Soviet interceptors and foreign fighters deployed in the early 1970s. Besides, the capability of Soviet interceptors is insufficient against low-altitude targets. Therefore, in the early 1970s the fourth-generation interceptors and fighters with outstanding maneuverability and

low-altitude performance began to be developed. In the years 1974-1977, test flights of three new models (Lamu J, Lamu K and Lamu L) were conducted successively. Lamu J is a subsonic ground attack plane with large bomb carrying capacity, high firepower, and high survival capability. In the other two interceptors models (Lamu K and Lamu L), the principal performances improved are higher maneuverability, as well as advanced radar and medium-range air-to-air missiles. Moreover, the models gained the capability of sighting and firing below the horizon and simultaneous tracking and attacking multiple targets.

Before the mid-1950s, the USSR executed the strategy of strengthening the active defense and prevention of aggression by the enemy; therefore, interceptors were the focus of development in aircraft deployment. In the mid- and late-1950s, the strategy of using rockets and nuclear weapons as the main force began to be carried out; however, the Soviets still stressed responses to enemy's nuclear attack bombers. Therefore, development of interceptors was still going on. So from the conclusion of World War II to the mid-1960s, air cover interceptors were consistently the development focus of Soviet aircraft. Out of more than 20 interceptor models developed in the USSR, 70 percent of them were designed according to air-cover requirements. These aircraft can be guided and commanded from the ground; therefore, the onboard equipment is simple and the weight is light. However, the maneuverability is good, with rapid climb rate and high firepower. In the mid-1960s, the USSR began to execute a strategy of flexible response, stressing that interceptors should be capable of executing multiple missions and ground attack capability. Both the onboard equipment and weapon system were improved; the aircraft bomb-carrying capacity and navigation range were increased, with higher penetration capability. Thus, the attack performance of interceptors is even more enhanced.

On average, a new generation of interceptors is developed in each decade in order to maintain the advanced capability of the combat equipment. Moreover, the number of interceptors are also emphasized. This is because, on one hand, the Soviets acknowledge that there still is a technical gap between Soviet interceptors and the advanced interceptors of the Western countries. Thus, the Soviets intend to compensate their technical inferiority with numerical superiority. Besides, the Soviets still remember the passive combat situation due to an insufficient number of interceptors in the first stage of Germany's invasion in World War II.

In modern warfare, the loss of aviation equipment is quite high. As estimated by the North Atlantic Treaty Organization (NATO), the loss of air force equipment will be 60-80 percent during the first 2 weeks of a war. The Soviets made an appropriate preparation according to this estimate. Now, the USSR maintains a production rate of new aircraft double that of the United States. In addition, old models are kept longer in deployment in order to maintain higher numerical superiority.

III. Analysis of Performance of Soviet Interceptors

1. Design trend

In military aircraft, the development of fighters (interceptors) is the most active, as the trend indicates the military idea of a nation or a bloc. When designing fighter planes, selections of wing loading and thrust-to-weight ratio are very important. Generally speaking, the data indicate the emphasis of design in fighter planes. Figure 1 indicates the distribution of combat wing loads and thrust-to-weight ratios of modern fighter planes, which do not carry objects outside the fuselage besides air-to-air missiles and half the fuel stored inside the fuselage. We can see from the figure that the distribution of wing loads and thrust-to-weight ratios follows a certain rule, since the fighter planes have different main missions.

Figures 2 and 3 show variations of combat wing loads and thrust-to-weight ratios for 30 years of fighter planes. It is clear from the data in the diagrams that the design of Soviet interceptors generally followed the West, lagging by 7-8 years.

2. Performance level (with no objects carried outside the fuselage other than air-to-air missiles)

1) Maximum level flight speed

Before the mid-1960s, there was no basic change in means of air battle for fighters, since the main weapon was still the machinegun firing directly. Although air-to-air missiles were deployed and utilized, the combat capability was still inferior, mainly pursuit and attack from the rear hemisphere. In this situation,

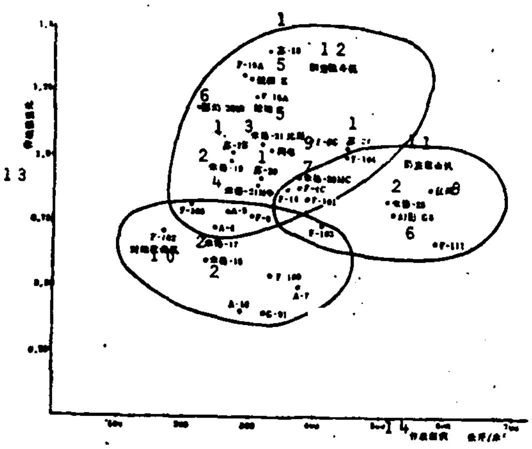


Fig. 1. Distribution of combat wing loading and combat thrust-to-weight ratio of fighter planes.
Key: (1) Su; (2) MiG; (3) MiG-21 BC; (4) MiG-21MF; (5) Lamu; (6) Phantom; (7) MiG-23MS; (8) Hurricane; (9) Lightening; (10) Ground attack planes; (11) Air cover interceptor planes; (12) Air control fighter planes; (13) Combat thrust-to-weight ratio; (14) Combat wing loading in kg/m^2.

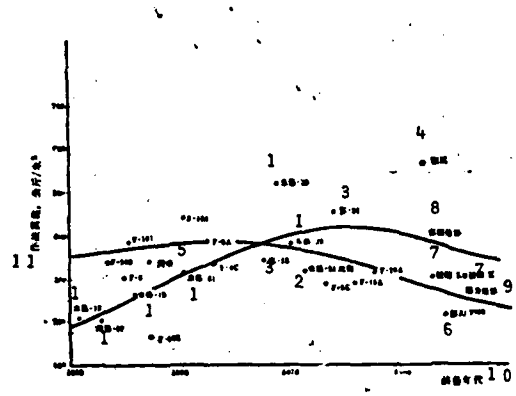


Fig. 2. Increment situation of combat wing loading of fighter planes.
Key: (1) MiG; (2) MiG-21 BC; (3) Su; (4) Hurricane; (5) Lightening; (6) Phantom; (7) Lamu; (8) Soviet trend; (9) Trend in the West; (10) Year of deployment; (11) Combat wing loading in kg/m^2.

aircraft with higher speeds naturally have advantages. Hence, from World War II to the mid-1960s, the speed of fighters doubled approximately every decade. Figure 4 shows the increase of the maximum level of flight of fighters. Since the 1960s, the variation in maximum Mach number of fighter planes has not changed much. Of course, both the Soviet Union and the United States mastered the technique of M3 speed for aircraft back in the 1960s. The SR-71 of the United States and MiG-25 of the USSR were deployed in sequence; however, these aircraft do not represent the main stream of development of fighter planes. With development of science and technology after better solving the problem of supersonic combat effectiveness of fighter planes, the Mach number of maximum level flight of fighters will be further increased.

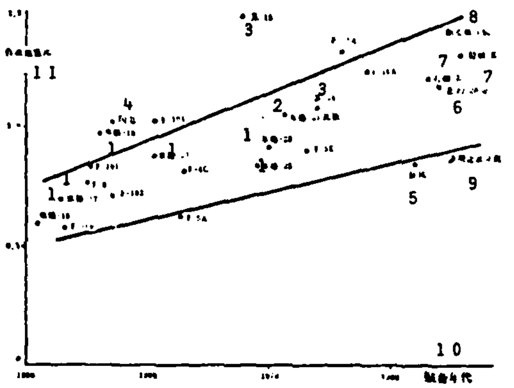


Fig. 3. Increment situation of combat thrust-to-weight ratio of fighter planes.
Key: (1) MiG; (2) MiG-21 BC; (3) Su; (4) Lightening; (5) Hurricane; (6) Phantom; (7) Lamu; (8) Air control fighter planes; (9) Multi-usage fighter planes; (10) Year of deployment; (11) Combat thrust-to-weight ratio.

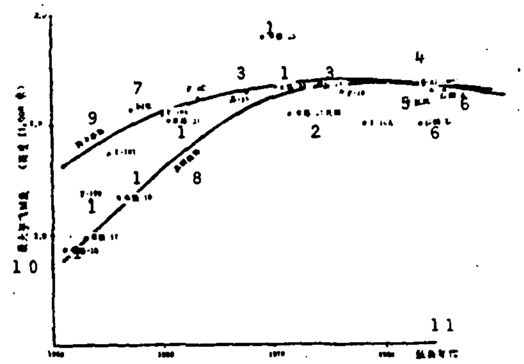
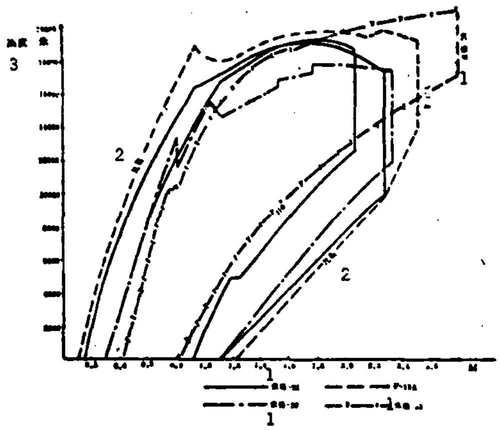


Fig. 4. Increment situation of maximum M number of fighter planes.
Key: (1) MiG; (2) MiG-21 BC; (3) Su; (4) Phantom; (5) Hurricane; (6) Lamu; (7) Lightening; (8) Soviet trend; (9) Trend in the West; (10) Maximum M number of level flight (altitude at 11,000 m); (11) Year of deployment.

2) Range of flight speed and altitude

Figure 5 shows flight envelopes of three major Soviet interceptors (MiG-21, MiG-23 and MiG-25). We can see that in improvement and design of Soviet interceptors, emphasis was given to raise the maximum low-altitude speed of the aircraft as the low-altitude performance of interceptors was also correspondingly improved. For comparison, the dotted lines in Fig. 5 show the flight envelope of the F-15A fighter plane of the United States. The technical gap between the Soviet and American fighters is apparent. Of course, the flight performances of the new generation Soviet interceptors, such as Lamu L and K, will be certainly enhanced. However, as seen from bits and pieces of data revealed in foreign countries, a conventional technique is still adopted in design. Hence, it can be assumed that the flight envelopes of Lamu L and K will not exceed the level of the F-15A.

3) Maneuverability



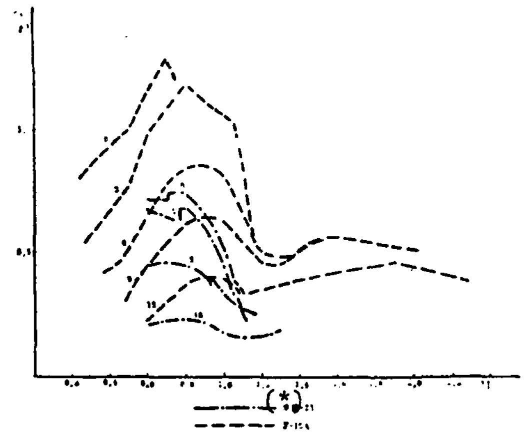


Fig. 5. Comparison of flight envelopes between MiG-21, -23, -25 and F-15A.
Key: (1) MiG; (2) BC; (3) Altitude in m.

Fig. 6. Vertical-direction horizontal acceleration performance of MiG-23 and F-15A.
Key: (*) MiG.

Figure 6 shows the vertical-direction acceleration characteristics of the MiG-23 and F-15A at different altitudes. Figures 7, 8, 9 and 10 show the level acceleration time, climbing speed, stabilization circling radii at high, medium and low altitudes for MiG-21 BC, MiG-23 and F-15A.

We can see from the above comparisons, if we say that the differences are not much in the maximum level flight speeds and ceilings between the Soviet interceptors and American fighters, that differences in maneuverability (affecting combat effectiveness directly) are obvious. While at a speed of M0.8, the climbing rates of MiG-21 BC, MiG-23 and F-15A are, respectively, 110, 114 and 243 meters per second; the stabilization circling angular velocities are 8.5, 8.5 and 14.1 degrees per second; the time required for one complete circle is, respectively, 42.4, 42.4 and 25.5 seconds; the time required from M0.8 to M1.2 is, respectively, 51, 40 and 18 seconds, and the time required from M0.8 to M1.4 is, respectively, 103, 66 and 38 seconds. Hence, in an air battle between the Soviet

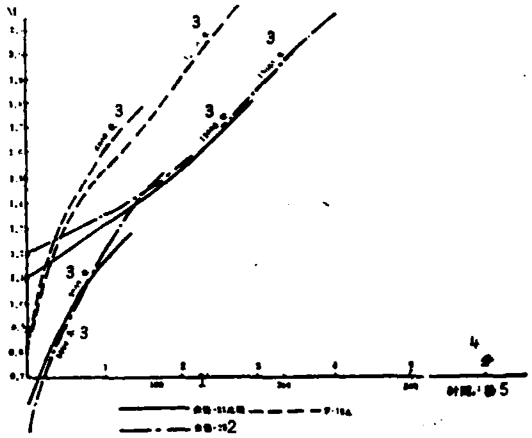


Fig. 7. Horizontal acceleration time of MiG-21 BC, MiG-23 and F-15A.
Key: (1) MiG-21 BC; (2) MiG-23; (3) Meters; (4) Minutes; (5) Time: seconds.

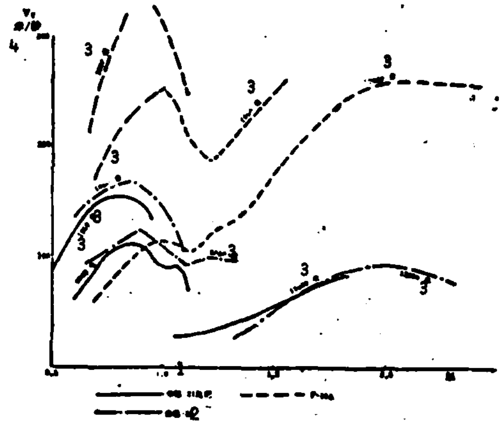


Fig. 8. Climb speeds of MiG-21 BC, MiG-23 and F-15A.
Key: (1) MiG-21 BC; (2) MiG-23; (3) Meters; (4) Meters per second.

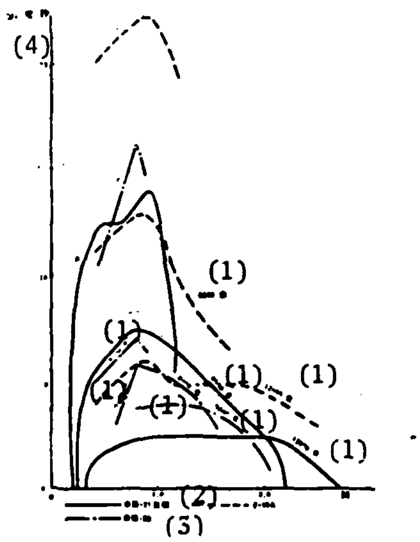


Fig. 9. Stabilization circling performance of MiG-21 BC, MiG-23 and F-15A.
Key: (1) Meters; (2) MiG-21 BC; (3) MiG-23; (4) Degrees per second.

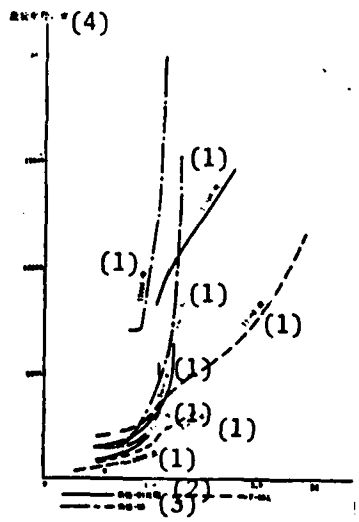


Fig. 10. Minimum stabilization circling radii of MiG-21 BC, MiG-23, and F-15A.
Key: (1) Meters; (2) MiG-21 BC; (3) MiG-23; (4) Circling radius in meters.

interceptors and the American F-15A, it is a foregone conclusion in favor of the American aircraft, if only judging from flight performance. This combat mission will be assigned to the Lamu L interceptors deployed in the mid-1980s.

3. Onboard radar

The avionics of the USSR is consistently a weak link. Even the second-generation MiG-21 interceptors were not equipped with all weather radar in the first stage of development. Although all weather radar was installed on other models, its performance was quite limited. The most recent model of the MiG-21, the MiG-21 BC model, has an improved version of the onboard radar, but the search distance is only 30 kilometers (km). For radar equipping the MiG-23MC (export model), the search distance is 20-25 km and the tracking distance is 14-17 km. The radar equipping the MiG-23C (domestic model) has better performance, with a search distance of 85 km and tracking distance of 54 km. Compared with that of the United States, the Soviet radar is inferior. Although the weight of the APG-63 radar on the American F-15A is the same as the radar equipping the MiG-23C, the searching distance of the American radar is more than 150 km with a wider search angle than the Soviet radar. Of course, the radar carried on the new generation Soviet Lamu L and K will be more advanced but the performance will not exceed that of the American radar.

4. Weapons

Generally, the Soviet interceptors are equipped with guns with a relatively high technical level. However, generally speaking, the firepower of the Soviet interceptors is relatively weak. For example, with an overall weight of nearly 18 tons the Soviet air-cover interceptor Su-15 is only equipped with two old-model air-to-air missiles; one of them uses radar guidance and the other, infrared guidance. Since the aiming accuracy of the Soviet weapon is somewhat inferior, the power of a single round is relatively high as compensation. However, the overall effectiveness of the weapon is not high. With the advancement of electronic techniques, dimensions and weight of Soviet air-to-air missiles will be further reduced for ensuring a certain performance. Thus, the firepower of Soviet interceptors will be correspondingly increased.

If an overall consideration of the technical level of fighters is made regarding combat performance, onboard equipment and weapon system, the Soviet interceptors lag behind those of the United States by more than 10 years. There are many causes: first is the weaker technical foundation in the USSR, which does its high level research in fundamental theories. However, studies on application of fundamental research to model development are quite weak; therefore, the technical reserve of model development is inadequate. Hence, most new techniques adopted by the USSR in development of new interceptors originate in the West, such as sweptback wings, variable sweptback wings, twin delta wings, S-shaped front-edge wings, adjustable twin air intake system, Doppler radar, radar for simultaneous searching and tracking of multiple targets, multiple-rotating-tube gun, dogfight missile, laser bomb, and napalm. The impression is that the Soviet Union follows the West in technology. As mentioned by the former defense minister (of the United States) Clement, "The Soviet Union does not have our technical foundation of varieties. It seems that they follow us in aircraft technology; there are no exceptions whatever in variable sweptback wings, modern firepower control, missile system, effective loading, or combat radius. The techniques we applied in the 1950s and 1960s were studied by them in the 1960s and 1970s." Secondly, the USSR concentrates on studying aviation science and technology with relative concentration of the aircraft design; thus, there is a lack of varieties in aeronautical studies and model development, affecting the accumulation of experiences and studies of newer techniques. In addition, the Soviet Union conducts relatively crude design of new aircraft, so the aircraft efficiency is generally on the lower side. For example, in designing the MiG-19, the Soviets used an average of 165 engineer-hours for each kilogram of air weight and 290 engineers took part in the design, these figures were much lower than the corresponding figures in the United States. While designing F-100A fighters in the United States, every kg of air weight used an average of 287 engineer-hours, higher by 74 percent than that of the Soviet Union while designing the same class MiG-19. In designing the F-100A, the participating engineers numbered 850 during the busiest period and the average number of engineers was around 550, which was 90 percent greater than that of the USSR in designing the MiG-19. Apparently, while designing a new fighter plane in the United States, the design work is more extensive, more detailed and more thorough than that in the USSR; therefore, the efficiency of the US fighter plane is higher than the corresponding Soviet plane.

IV. Development Down the Road

In the mid-1970s, the Soviet Union began to develop the fourth-generation interceptors, Lamu J, Lamu K and Lamu L; test flights of these planes were completed in the years 1974-1977. It is expected that these interceptors will be deployed in the mid-1980s. The Lamu L is a single-seat all weather air-cover interceptor with appearance like that of the F-18 of the United States. The Lamu L has a combat thrust-to-weight ratio of 1.2:1 and combat wing loading about 300 kg/m^2 with considerable enhancement of maneuverability. Besides a 30-mm gun, the Lamu L carries eight wire-guided air-to-air missiles; on the aircraft is installed a radar capable of simultaneous searching and tracking even of sighting below the horizon with a searching distance less than 150 km. The Lamu K is a twin-engine variable sweptback air-cover interceptor with appearance like the American F-14. The Lamu K interceptor has a combat thrust-to-weight ratio of 1.3:1 and a combat wing loading about 300 kg/m^2, with a radar installed like theAWG-9 of the American F-14; the radar can sight and track below the horizon and is capable of simultaneous searching and tracking of multiple targets. Besides a 30-mm gun, the Lamu K carries six advanced air-to-air missiles. The Lamu J is a subsonic twin-engine ground attack plane with performance like that of the American A-10. The Lamu J carries a 30-mm six-rotating-tube gun; its ten hanging frames beneath the fuselage carry bombs, rockets and air-to-ground missiles. The maximum bomb carrying capacity is five tons.

The Lamu J, Lamu K and Lamu L, as well as the presently deployed MiG-23, MiG-25, Su-24 and their remodeled versions will be the main force of Soviet fighter planes in the 1980s and 1990s. According to forecast, a newer generation of interceptors will be developed in the USSR in the late 1980s; the new interceptors will adopt some presently available new technology with further enhancement of maneuverability; however, improvements of the onboard equipment and weapon system will be more pronounced. In addition, by the end of this century the Soviet Union may develop supersonic interceptors with even better combat performance. Before that, improvements on the MiG-25 and Su-24 are possible in order to temporarily satisfy the demands of supersonic air combat.

SCIENCE DISCUSSION MEETING OF THREE-COORDINATE SURVEYING MACHINE

Qin Zongwang

The three-coordinate surveying machine is a comprehensive precision instrument with wide applications; this is a necessary key equipment for computer aided design (CAD) and computer aided manufacture (CAM) of aircraft and their engines. The aviation circles of world countries pay great attention to the surveying machine.

In order to promote development of a three-coordinate surveying machine in China to satisfy the demands of aviation and other manufacturing industries, from 19 to 24 December 1981, China's first Three-coordinate Surveying Machine Technique Discussion Meeting was convened by the China Instruments and Meters Society at the Aviation Precision Institute with 103 delegates attending.

Although 42 papers were received at the meeting and were read either at the general meeting or at section meetings. These papers describe the developmental trend of three-coordinate surveying machines both at home and abroad, with precision analysis, machine structure, examination methods, probes of various types, a display device of examination data, hardware joint design, computer software and its applications.

At the meeting, it was proposed to prescribe a developmental plan for the three-coordinate surveying machine in China, erection of production plants, and

drafting of state certification regulations of three-coordinate surveying machines. In addition, a three-coordinate surveying machine section was proposed to be established in order to strengthen the circulation of technical information.

DEVELOPMENT OF DOUBLE-ROTOR SUPERCHARGED TURBOJET ENGINES IN THE USSR AS SEEN FROM MODELS R11 TO R29

Liu Chunyi

In the USSR the main interceptor planes mostly use double-rotor supercharged turbojet engines. For a period of more than two decades, the Soviets improved these engines incessantly to attain a relatively high level technology of double-rotor engines. This is not only revealed in the performance of the turbojet engines, but also in operational reliability. The Soviets engaged in a technical development route different from that of the Western countries.

Formation of Design Idea

The development of the aviation industry technology of a nation should be subject to its overall strategic idea and the strategic principle matching its technical level. The Soviets show their characteristics in the development of engines.

In the early 1950s, with the dawn of jet engines, the jet fighter planes of the USSR and the United States competed in high-altitude and high-speed development in order to gain air superiority.

With its eyes on world expansionist strategy, the United States stresses ground attack capability and navigation range of tactical fighter planes; thus,

the development of turbofan engines was started. In the early 1960s, the development of turbofan engines in the Western countries entered a vigorous phase. Later, the United States performed detailed tests on the problem of matching air intake passage and engine to attain better perfection in performance of the practical turbofan engines in this generation of development.

In the 1950s, the Soviet Union carried out an active defense strategic principle; therefore, it stressed development of light front-line interceptors and high-altitude high-speed interceptors with simple equipment, low fuel tank capacity, and relative short navigation range. This type of aircraft requires a thrust-to-weight ratio as high as possible, but high thrust magnitude is not required. Therefore, during design often small flow and low total compression ratio are adopted in order to attain high unit thrust. The above-mentioned tactical requirements led to the production of the R11F-300 supercharged turbojet engines.

The prototype aircraft of the R11F series is estimated to have been developed in the early 1950s; in 1956, the MiG-21 aircraft was formally deployed. Technically, this is an important breakthrough from the PD-9B to the R11F-300. This not only solves the design problem of the double-rotor structure, but also is a great enhancement in the technical level of engine components, especially the design of air compressors. The R11F-300 engine is equipped with a six-stage air compressor with three stages each for high and low pressures. The designed compression ratio is 8.85 and the average ratio of pressure increase in one stage is 1.438. The M number at the blade tip of the first stage is 1.36; this is the first practical turbojet engine in the world adopting supersonic blades. These breakthroughs enabled the R11F-300 to be one of the outstanding performance engines in the early 1960s, exceeding the British and American engines (such as the J57, J75, J79, and Olympus) and became prototypes of the later double-rotor Soviet turbojet engines, such as the R11F2-300, R11F2S-300 and R13-300.

In the mid-1960s, the Soviet strategic idea turned from defense to expansion; thus, the design of fighter planes was turned to heavy weight, long navigation range, and strengthening of ground attack capability, with requirements for engines of large thrust and high thrust-to-weight ratio. While developing this type of engines in the USSR, considerations were given to the possible domestically attainable technical level, so the Soviets did not follow the development route

in the West of turbofan engines, but utilized their superiority in the sphere of double-rotor turbojet engines. From the R11F-300 the R29-300 was derived. The double-rotor technique was used to successfully develop the AL21F-3. Thrusts of these engines are greater than 11,000 kg, becoming one of the interceptor engines with the highest thrust. The AL21F-3 engines were installed on the MiG-23, Su-20 and Su-24 ground attack planes, strengthening the power of air force and navy. Besides, the Soviet Union absorbed an American development lesson that the matching problem was not considered between the aircraft and engines in the development of the F-111. Thus, the Soviets vigorously engaged in improvements of operational reliability of R11F-300 engines for as long as ten years, obtaining an apparent result.

In the late 1960s, on the technical foundation of the R13-300 engines, the Soviets developed the R25-300, which was installed on MiG-21 BC aircraft in 1974. At the same time, they developed two dogfight aircraft (Lamu K and Lamu L) like the American F-16 and F-18, as well as the Lamu J ground attack plane, which uses the R13-300 engine. It is assumed that the two former aircraft also use double-rotor turbojet engines.

From the above mentioned, we can discover that any change in Soviet interceptor generation or the application of technical results is related to their solid technical foundation of double-rotor turbojet engines. The sufficient utilization of technical inheritance and incessant improvement and adoption of new techniques show the reason for their attainment of successful development.

Variation of Engine Performance Parameters

Unit parameters: Figures 1, 2, 3 and 4 show the variation trend of ground thrust-to-weight ratio, fuel consumption rate, unit thrust, and unit frontal thrust of engines. From the diagrams concerning the R11F-300 in two decades the thrust-to-weight ratio of Soviet engines was increased by 30 to 35 percent; in the first decade, the increase was only 9 percent. For engines in the West, with the exception of the M53-5, their ground thrust-to-weight ratios have certain advantages.

As for the supercharged fuel consumption rate, it was reduced by 20 percent for Soviet engines; this result is better than that of the turbofan engines in the

West. However, the fuel consumption rates (at the aximum power) of Soviet engines are not as good as those of turbofan engines.

As far as unit thrust, the Soviet engines have been increased 26%, superior to that of turbofan engines of the West. But in the previous decade if has increased only 9.5%.

As far as unit frontal tnrust, the Soviet engines have been increased 50%, far superior to the turbofan engines of the West. However, in the previous decade it was also only 15%.

From the developmental trend of the unit parameters, they are generally the same between the Soviet double-rotor engines and turbofan engines in the West; the overall parameters generally match between the Soviet Union and the Western countries. Although there is superiority in the thrust-to-weight ratio in turbofan engines in the West, the operational reliability remains a problem but is improving continuously.

Worth particular attention is that before the appearance of R13-300 engines, the improvement of performance of Soviet engines was very small. This is explained by the fact that the Soviets mainly exerted their efforts at that time in improving the operational reliability, which affected enhancement of performance.

Variation of flight performance due to aircraft engine: the thrust-to-weight ratio during flight can be used to describe the altitude-speed performance of aircraft engines. Figure 5 explains that the thrust characteristics of Soviet

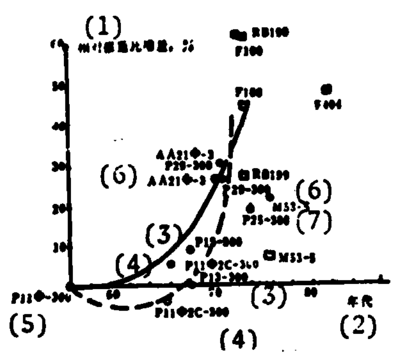


Fig. 1. Variation of ground thrust-to-weight ratio: solid line indicates full power; ■ and • are data points; dotted line indicates the maximum state; □ and o are data points.
Key: (1) Relative increment of thrust-to-weight ratio; (2) Year; (3) R13-300; (4) R11F2S-300; (5) R11F-300; (6) R29-300; (7) R25-300.

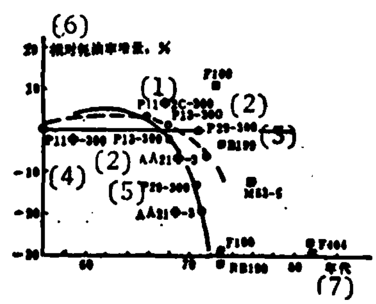


Fig. 2. Variation of ground fuel consumption rate: solid line indicates full power; ■ and • are data points; dotted line indicates the maximum state; and □ and o are data points.
Key: (1) R11F2S-300; (2) R13-300; (3) R29-300; (4) R11F-300; (5) R29-300; (6) Relative increment of fuel consumption rate; (7) Year.

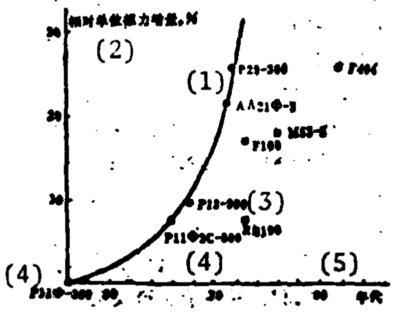


Fig. 3. Variation of unit thrust.
Key: (1) R29-300; (2) Relative increment of unit thrust; (3) R13-300; (4) R11F2S-300; (5) Year.

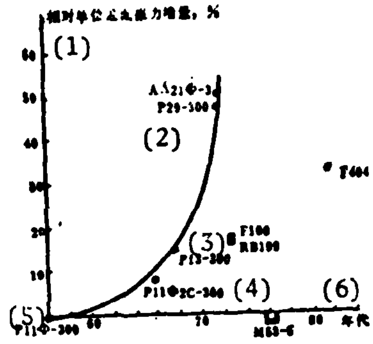


Fig. 4. Variation of unit frontal thrust.
Key: (1) Relative increment of unit frontal thrust; (2) R29-300; (3) R13-300; (4) R11F2S-300; (5) R11F-300; (6) Year.

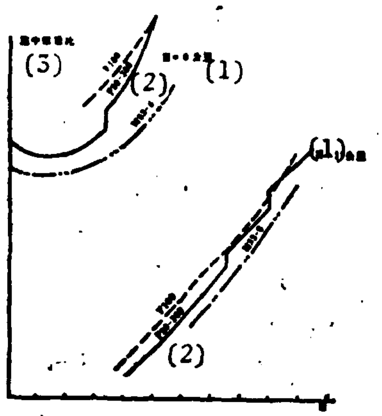


Fig. 5. Variation of thrust performance in air.
Key: (1) Km; (2) R29-300; (3) Thrust-to-weight ratio in air.

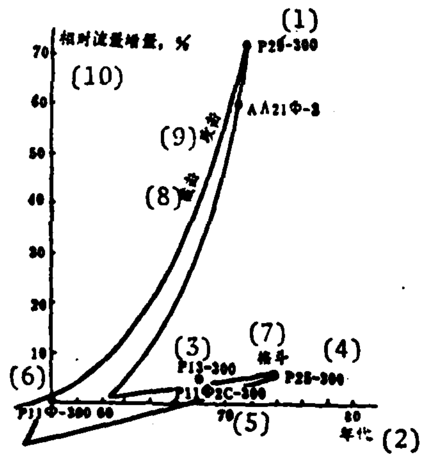


Fig. 6. Variation of stream flow in engine.
Key: (1) R29-300; (2) Year; (3) R13-300; (4) R25-300; (5) R11F2S-300; (6) R11F-300; (7) Dogfight; (8) Interception; (9) Attack; (10) Relative increment of stream.

double-rotor engines vary considerably; thrusts increase rapidly with increase of M. At low speed flight over the sea surface, the performances are lower than that of the American F100 engines. However, the differences decrease with increasing M number. At an altitude of H=11 km, the performance of Soviet double-rotor engines

corresponds to that of F100 engines; this is a very good characteristic. Compared to the French M53-5 engines, the Soviet engines are superior from an overall standpoint.

Variation of Engine Thermal Parameters

Figures 6, 7, 8, 9 and 10 show the situation of variation of engine thermal parameters. We can see from these figures that in the first decade the increase of air flow was little, but the increase was considerable in the second decade. The increase of air flow is mainly for raising the thrust magnitude of the engine. However, compared to turbofan engines in the West, the required air flow of the Soviet double-rotor engines is considerably smaller with the same thrust magnitude.

The increase of overall compression ratio of Soviet engines is about 80 percent. In order to reduce the fuel consumption rate, the Soviets adopted a medium overall compression ratio. However, in the West the total compression ratio is about 25.

Over the years, the increase in T_3^* of the Soviet engines was 20 percent, lower by 10-15 percent than for engines in the West. The increase in supercharged temperature was 12 percent for the Soviet engines; this figure corresponds to that in the West as the figure approaches the limiting combustion temperature of fuel oil.

Air compressor: Figure 11 indicates the variation of mean stage pressure. We can see from the figure that in order to solve the problem of steady operation of double-rotor turbojet engines, the Soviets adopted a method of reducing the average stage pressure ratio. The oscillation tolerance of the air compressor was increased from 9 to 20 percent.

In order to improve the capability of the air compressor to counter the abnormal variation of oscillation, the Soviets adopted a technique of casing treatment which is simple and reliable. After casing treatment, efficiency of air compressor is reduced by 1 percent, but the oscillation tolerance in the abnormal-variation flow field is doubled. Besides, because of continually increasing the chord length of the first stage blade and reduction of the aspect ratio

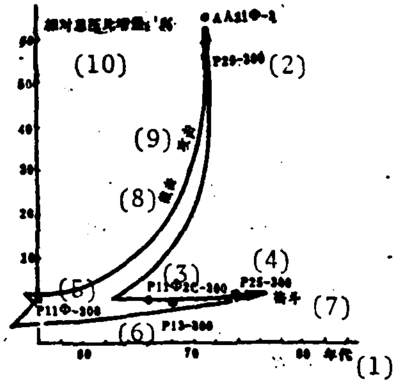


Fig. 7. Variation of total engine pressure.
Key: (1) Year; (2) R29-300; (3) R11F2S-300; (4) R25-300; (5) R11F-300; (6) R13-300; (7) Dogfight; (8) Interception; (9) Attack; (10) Relative increment of total pressure ratio.

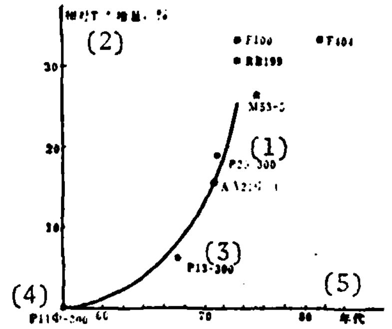


Fig. 8. Variation of supercharger temperature.
Key: (1) R29-300; (2) Relative increment of T_1^*; (3) R13-300; (4) R11F-300; (5) Year

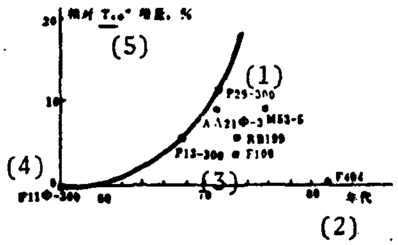


Fig. 9. Variation of supercharger temperature.
Key: (1) R29-300; (2) Year; (3) R13-300; (4) R11F-300; (5) Relative increment of T_4^*.

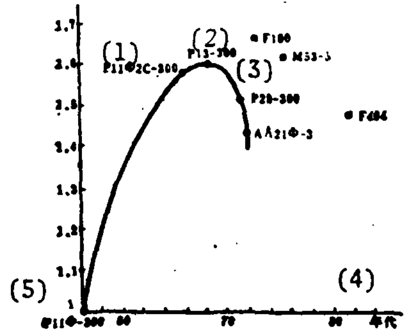


Fig. 10. Variation of supercharging pressure ratio.
Key: (1) R11F2S-300; (2) R13-300; (3) R29-300; (4) Year; (5) R11F-300.

(to as low as 1.86 in some cases), the oscillation boundary of the blades expands at high velocity and pressure. In addition, the dynamic response of the blade to turbulent flow is delayed.

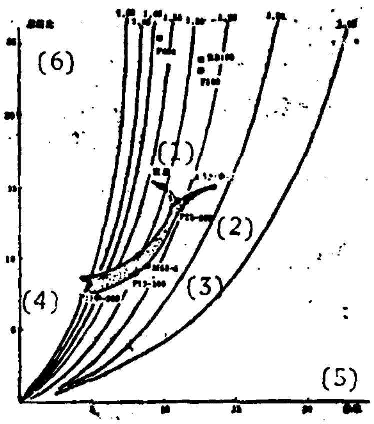


Fig. 11. Variation of mean stage-pressure-ratio of air compressor.
Key: (1) Development; (2) R25-300; (3) R13-300; (4) R11F-300; (5) Number of stages; (6) Total pressure ratio.

Since blades rotate at supersonic speed and there is the effect of casing treatment, the efficiency of the air compressor is low. In recent years, the improvement of efficiency of air compressors in the USSR was little, lower by 5-6 percent than that in the West. The lower efficiency is equivalent to a loss of 7-8 percent of thrust.

Combustion chamber: the coil tubes in the combustion chamber of the Soviet engines are gradually developing toward ring and short ring shapes. The Soviets continually increased the air intake pressure and reduced flow speed to expand the operational boundary. For example, in the development from the R11F-300 to the R29-300, the flow velocity in the combustion chamber is reduced from 216 to 158 m/sec, and the flow velocity in the flame cylinder reduced from 70 to 42 m/sec. In order to enhance the quality of fuel atomization, the Soviets gradually changed the centrifugal-type dual-nozzle to a pneumatic nozzle. However, the development of the short-ring combustion chamber in USSR has been slow.

Turbine: the technique of counterflow and impact cooling has been applied on turbine blades of Soviet engines; a practical effect of 250°C temperature

reduction was obtained. However, this reduction is still 100-150°C behind the current level in the West. The Soviets adopted a method of cooling air flow by adjusting turbine blades; thus, the turbine efficiency is increased and fuel consumption rate is further reduced. It was reported that the Soviets are experimenting and studying other cooling techniques.

Supercharged combustion chamber: at the beginning, the flame stabilizer of the supercharged combustion chamber of the R11F-300 engines was a ring-shaped "V" channel type; later, it was changed to a diametral-direction radial type. Finally, a diametral-direction and radial-direction multi-row compounding type stabilizer was adopted with use of a cone expander and shunt ignition to increase the temperature of the core region. In the supercharged combustion chamber, a ring-by-ring and pressure-stage by pressure-stage fuel supply technique is used with soft ignition. The nozzle can be automatically adjusted at full load conditions.

With increasing supercharger temperatures, the short anti-vibration screen in the supercharged combustion chamber of the R11F-300 engines was changed to a full length anti-vibration screen. The cooling air flow passes through numerous tiny holes on the sandwich wall to form air films to cool the supercharger cylinder.

Adjustment rule of engines: in order to simultaneously meet requirements of performance and reliability, the Soviets changed the adjustment rule of double-rotor engines. At the beginning, the principal adjustment program of the R11F-300 included the requirement that the nozzle area F_c=constant and the low-pressure rotor rotating speed n_1=constant, and the supercharger adjustment program included the requirement that the nozzle area $F_{c\phi}$=constant and the turbine expansion ratio π_T^*=constnat. At high altitudes, during supercharging the p_2 atmospheric-pressure adjuster operates to limit fuel supply to the supercharger. By using the principal adjustment program with F_c=constant and n_1=constant, the adjustment is especially suitable for high-speed flight in order to match the three-stage adjustable cone program of air intake passage of the MiG-21 aircraft. Since the range of the converted rotating speed is small, it is also advantageous to ensure steady operation of the air compressor. However, this adjustment program has a certain effect on low-speed performance and T_3^* and T_4^* increase with T_1^*; thus, the problem of superheating is also likely to occur.

Later, the Soviets changed the three-stage adjustable cone program to a compounding adjustment program. With varying T_1^*, n_1 is equal or not equal to a constant (n_2 is equal to a constant), and the nozzle area is equal or not equal to a constant. At the same time, T_4^* is also adjusted accordingly. In order to prevent an engine running over the rated speed, n_2 is often limited to a certain value. This adjustment program takes advantage of three fundamental adjustment programs (n_1=constant, T_3^*=constant, and n_2=constant) and simultaneously takes care of high and low speed performance to ensure steady operation of the air compressor and not to exceed the rated temperature of the turbine. Therefore, the potential of the engine can be exploited. Later, the supercharger combustion chamber also adopted the compounding adjustment program; for example, when $T_1^*<288°$K, π_T^* = constant. When $T_1^* \geq 288^oK$, π_T^* = constant $F_{c\phi}$ _ constant , but thrust boost fuel feed varies according to the rule $\frac{G_{T\phi}}{P_2^*}$ = constant. When P_2 is too low, in order to prevent thrust boost fluctuation, the system automatically increases the amount of fuel supplied to the afterburner.

Some points are worthwhile to mention in that the Soviets usually adopt ways of exceeding the rated temperature and revolution, as well as additional fuel supply in the adjustment system in order to enhance flight performance. For example, at $M \geqslant 1.5$ for the case of R13-300 engines, the secondary supercharging is automatically connected. This not only increases the thrust, but also enhances operational stability of supercharging. For another example, in the case of R29-300 engines, when $T_1^* = 40^oC$, n_1 overspeeds 2.5%; when $T_1^* = 85^oC$, 6% additional fuel is supplied to the afterburner, and all is for this purpose.

Another characteristic is adjustment while cruising with the engine revolution reduced from 93 to 90 percent of the rated revolution. The temperature adjuster automatically adjusts T_4^* to the lowest value. The nozzle opens wider and the turbine throttles about one half of the cooling flow. At that time, the cruising fuel consumption rate of the double-rotor turbojet engine can be reduced to about 0.82; this figure approaches the fuel consumption-performance of the turbofan engines to increase the subsonic navigation range.

Guiding Nozzle

As a practice in the Western nations, guiding nozzles are installed on an engine, while in the USSR the guiding cover is installed in the aircraft tail cover, which is not adjustable and combines with the engine main nozzle into a simple convergent jetting guidance device. The secondary flow required by the jetting guidance device of the R11F-300 engines is approximately 7 percent of the main flow. At high speeds, the increment of thrust is about 8 percent. At low speeds, a suction is created at the tail portion in order to assist cooling of the engine casing. At that time, loss of thrust is about 3 percent. This jetting guidance device is simple and reliable with low weight, but its transonic performance is poor. Later, since the thrust loss at the nozzle is increased with increasing M number, for MiG-23 aircraft the convergent-divergent type guiding nozzle in the aircraft tail cover was used. This nozzle is a gas-float type and the aircraft tail cover can be automatically adjusted by the pressure difference between the main flow and the flow at the tail portion of the aircraft. It was claimed that this gas float type guiding nozzle was used for the first time ever. This type of nozzle was experimented with by Americans in the F-102 aircraft, but the experiments failed. In designing a gas-float type guiding nozzle, problems of thrust performance and high-temperature deformation should be solved. In particular, the matching problem between the primary and secondary flows is the most important. Hence, this type of nozzle is worth studying extensively.

Application of Titanium Alloys

Generally, no titanium alloys are used in R11F-300 engines. In R29-300 engines, the quantity of titanium alloys used is about 20 percent of the total weight of the engine. In particular, for the air compressor part, the quantity of titanium alloys amounts to 50 percent of the total weight of the part. Compared with applications in the West, the use of titanium alloys in Soviet engines is lower by 10 percent.

Engine Service Life

The service life to first overhaul of the prototype of R11F-300 engines was 100 hours; later, the service time to first overhaul was gradually lengthened to 200 hours. For the double-rotor turbojet engines installed in the Soviet interceptors, the standard service time to the first overhaul is 200-250 hours; in

some cases, it may exceed 300 hours. These figures are considerably lower than these in the West.

After R11F-300 began operation, an important breakthrough was attained in the Soviet double-rotor supercharged turbojet engines. At present, the ground thrust-to-weight ratio of Soviet engines is lower than that in the West; however, the overall performance of Soviet engines is not inferior. The potential for development of Soviet double-rotor engines is quite large. After the operational stability of the engines is solved, the mean stage-pressure-ratio of Soviet designed engines may have an increasing trend. Besides, the Soviets strive to raise the combustion gas temperature in front of the turbine, to shorten the length of the combustion chamber, and to adopt an electronic adjustment technique for the engine. Not long afterwards, the thrust-to-weight ratio of a double-rotor supercharged turbojet engine may approach 8. Without doubt, even in the 1990s the Soviet interceptors will still mainly rely on double-rotor supercharged turbojet engines. It is assumed that this trend will not change in the immediate future.

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